

# Examining the Location of the Magnetopause in an Undergraduate Lab

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(Dated: June 13, 2007)

## Abstract

Integrating areas of current research into undergraduate physics labs can be a difficult task. The location of the magnetopause is one problem that can be examined with no prior exposure to space physics. The magnetopause location can be viewed as a pressure balance between the dynamic pressure of the solar wind and the magnetic pressure of the magnetosphere. In this lab students examine the magnetopause location using simulation results from BAT-R-US global MHD code run at NASA's Community Coordinated Modeling Center. Students also analyze data from several spacecraft to find magnetopause crossings. The students get reasonable results from this lab as well as exposure to the tools and techniques of space physics.

PACS numbers: 94.30.ch, 94.30.Bg

Keywords: magnetopause, magnetosphere, solar wind, spacecraft data, MHD modeling, space plasma, undergraduate lab

## I. INTRODUCTION

Physics laboratory courses often emphasize experiments that relate directly to physical concepts being covered in lecture courses that students are taking concurrently. These experiments are intended to allow students to see for themselves how physical concepts work in the real world. Experiments of this sort tend to deal with physics that has been understood for some time and often involve performing classic experiments of the past. Experiments of this type do add to student understanding, but a steady diet of them can leave students disconnected from the current practice of physics. Maintaining the students' intellectual curiosity about science is a key to retaining students in science majors.<sup>1</sup> One way to maintain that curiosity is to create experiments that expose students to areas of current research to go along with classical experiments.

Designing experiments that deal with areas of current research and are accessible to undergraduate students can be a difficult task. This task is particularly difficult for space physics because most students have had little exposure to space and plasma physics. Space physics applications are often complex, defying simple treatment, and they often rely on advanced electricity and magnetism, which students often have late in their undergraduate curriculum.

In this paper we will discuss our use of the location of Earth's magnetopause as a topic for a lab for physics majors. The magnetopause is defined as the boundary between Earth's magnetic field and the interplanetary magnetic fields. The magnetopause is an appealing topic for a lab because it can be introduced at a fairly elementary level as a pressure balance, after which more complicated models can also be examined. This lab involves examining magnetopause location using computer simulations and spacecraft data.

In Sec. II we introduce some background information regarding the magnetosphere in general, and the magnetopause in particular. The portion of the lab using computer simulation to examine the magnetopause location is discussed in Sec. III, while the portion of the lab using spacecraft observations is discussed in Sec. IV. Conclusions as well as ideas about similar sorts of labs are examined in Sec. V.

## **II. MAGNETOSPHERE INTRODUCTION**

### **A. The Magnetosphere and the Magnetopause**

The structure and behavior of the area of space just outside of the Earth's neutral atmosphere is a problem that physicists have worked on for quite some time. The first clues to the nature of this region, now known as the magnetosphere, came from observations of the magnetic field on the Earth and observations of comets.<sup>2</sup> Though the Earth's magnetic field had been used since ancient times for navigation, in 1600 William Gilbert was the first to propose that the Earth was a giant magnet.<sup>3</sup> Serious observations of the Earth's magnetic field in the 1700s led to the discovery of variations in the magnetic field of the Earth called magnetic storms.<sup>4</sup> Magnetic storms were long hypothesized to be due to the Sun.<sup>5</sup> It took some time to arrive at a suitable mechanism<sup>6</sup> for the Sun to be affecting the magnetosphere, but it is now known that the solar wind causes magnetic storms. Comets were seen to have two tails: one caused by light from the Sun, the other by a stream of particles from the Sun, now called the solar wind.<sup>7,8</sup>

The magnetic field of the Earth acts as an obstruction to the solar wind, causing a shock called the bow shock and a boundary region called the magnetosheath (see Figure 1). The interaction with the solar wind compresses the Earth's magnetic field on the side of the Earth toward the Sun and stretches it on the side away from the Sun, resulting in the asymmetrical shape of the magnetosphere. As a first approximation, the location of the magnetopause is set by the balance between the dynamic pressure of the solar wind and the magnetic pressure of the magnetosphere. Variations in the solar wind lead to movements in where the magnetopause is located, as well as variations in the magnetic field measured on Earth. Currents within the magnetosphere and ionosphere also affect the magnetic field measured on Earth.<sup>9</sup>

The existence of a magnetosphere with a magnetopause of this sort was first posited to help explain variations in the readings of Earth-bound magnetometers<sup>10</sup> and to tie those variations to processes on the Sun. After these predictions, early spacecraft missions confirmed the existence of both the magnetosphere and the magnetopause.<sup>11</sup> Since that time there has been advancement in the observation, theory, and modeling of the location of the magnetopause. Recent models attempt to fit spacecraft observations of the magnetopause location and solar wind conditions to a variety of functional forms.

## B. Magnetopause Pressure Balance

As mentioned above, the location of the magnetopause can be considered to be due to the pressure balance between the dynamic pressure of the solar wind and the magnetic pressure of Earth (see Figure 2):

$$2\rho_{sw}(v_{sw} \cos \theta)^2 = \frac{1}{2\mu_0} B_{inside}^2. \quad (1)$$

where  $\rho_{sw}$  is the mass density of the solar wind,  $B_{inside}$  is the magnetic field inside the magnetopause, and  $\theta$  is the angle of incidence of the solar wind (the  $v_{sw} \cos \theta$  term is the solar wind speed normal to the magnetopause).

It turns out that due to the compression of the magnetosphere  $B_{inside}$  is not simply the dipole magnetic field of the Earth:

$$B_{dipole} = B_o \left( \frac{R_E}{r} \right)^3, \quad (2)$$

where  $B_o$  is the surface magnetic field at the equator,  $R_E$  is the radius of the Earth, and  $r$  is the distance from the center of the Earth to the location of interest. In this Chapman-Ferraro Model<sup>10</sup> for the magnetopause boundary location, there is a current that runs tangential to the magnetopause boundary in the dawn to dusk direction. This current causes a magnetic field that cancels the magnetic field of the Earth just outside the magnetopause, and doubles the magnetic field inside the magnetopause<sup>9</sup> so that:

$$B_{inside} = 2B_{dipole} = 2B_o \left( \frac{R_E}{r} \right)^3. \quad (3)$$

Combining Eqs. 1, 2, and 3 and solving for the location of the magnetopause leads to:

$$\frac{r}{R_E} = \left( \frac{B_o^2}{\mu_o \rho_{sw} (v_{sw} \cos^2 \theta)} \right)^{\frac{1}{6}}. \quad (4)$$

Assuming that solar wind consists of protons and electrons coming in normal to the magnetosphere and substituting in typical values of 10 protons/cm<sup>3</sup> and 400 km/s, Eq. 4 gives a distance to the magnetopause subsolar point,  $r_o$ , of roughly 8  $R_E$ . (The subsolar point is the location on the magnetopause along the line from the Earth to the Sun.) The observed value is for those conditions is 10.  $R_E$ .

A more thorough empirical expression including several factors ignored above and taking  $\theta = 0$  is

$$r_o(R_E) = 107.4 (n_{sw} v_{sw}^2)^{-\frac{1}{6}}. \quad (5)$$

In Eq. 5,  $r_o$  is the distance from the center of Earth to the magnetopause subpolar point in  $R_E$ ,  $n_{sw}$  is the number density of the plasma in the solar wind in  $\text{cm}^{-3}$ , and  $v_{sw}$  is the speed of the solar wind in  $\text{km/s}$ .<sup>12</sup> Note that this expression has the same dependence on solar wind speed and number density as Eq. 4, but a different leading constant.

### C. Recent Magnetopause Modeling

Much work has been done on modeling the location and shape of the magnetopause since Chapman and Ferraro's original model.<sup>10</sup> Along with the dynamic pressure of the solar wind, it was found that the orientation of the interplanetary magnetic field plays a key role in determining the shape of the magnetopause.<sup>13</sup> More recent studies have concentrated on using databases of magnetopause crossings of various spacecraft and the solar wind conditions at those times to formulate empirical expressions for the magnetopause location.<sup>14,15</sup> In the lab described here we use fits from the work of Shue et al.<sup>16,17</sup>

$$r = r_o \left( \frac{2}{1 + \cos \theta} \right)^\alpha \quad (6)$$

$$r_o = (10.22 + 1.29 \tanh [0.184(B_z + 8.14)])(D_p)^{-\frac{1}{6.6}} \quad (7)$$

$$\alpha = (0.58 - 0.007B_z)[1 + 0.024 \ln(D_p)] \quad (8)$$

In those Eqs. 6–8,  $r$  is the distance from Earth to the magnetopause boundary in  $R_E$ ,  $r_o$  is the distance from Earth to the subsolar point of the magnetopause in  $R_E$ ,  $B_z$  is the  $z$ -component of the solar wind's magnetic field in nT,  $D_p$  is the dynamic pressure of the solar wind in nPa, and  $\alpha$  is a unitless number representing the amount of tail flaring on the night side of the magnetosphere.

### III. MAGNETOPAUSE LOCATION FROM SIMULATION

In this portion of the lab students perform computer simulations using various solar wind conditions and determine where the subsolar point of the magnetopause is from their results. These results are fit to an expression of the form of Eq. 5, with the leading constant as a free parameter. The students compare their constant to the value of 107.4 from Eq. 5.

## A. Simulation Environment

The students model the magnetosphere by running the BAT-R-US<sup>18</sup> simulation on supercomputers at the Community Coordinate Modeling Center (CCMC). BAT-R-US solves the 3D magnetohydrodynamics equations in finite volume form using an adaptive grid. The simulation is run on NASA supercomputers at the CCMC where simulation runs can be requested by the public. Results from the simulations can be explored and visualized through the use of a standard web browser. The documentation provided is quite thorough, so explaining to students how to request a run and access the results is relatively easy. The resources that CCMC provides allow for access to powerful simulations without the need to have local access to supercomputer hardware or to install and maintain simulation codes.

## B. Finding the Magnetopause Location in Simulation Results

In the process of finding the subsolar point of the magnetopause in their simulation results, each lab group was required to come up with their own standards for determining the magnetopause location. The lab materials explain what processes will be going on near the magnetopause and how that might affect the students' graphs, but no prescription for finding the magnetopause is given. The task of defining their own standards serves several purposes. The students are stimulated by this requirement to examine their graphs more closely than they would be if a prescriptive method for finding the magnetopause were given. Furthermore, the openness of this task is a fair reflection of real lab work since interpretation of simulation results often requires discretion.

The instructions regarding finding the magnetopause location advise the student to look at more than one plasma parameter when finding the magnetopause, since the magnetopause should be evident in more than one type of data. Since the magnetopause is defined as the boundary between where the sun and the earth's magnetic fields dominate, it is clear that a signal should be visible in the magnetic field results. The magnetopause also affects the motion of the plasma particles, so differences in the plasma bulk velocity and number density should also be visible.

Figure 3 shows an example of data used by students to find the subsolar point of the magnetopause. On this plot, the magnetopause is located at roughly  $11 R_E$ . In the number density plot, the bump in the number density corresponds to the buildup of plasma in the magnetosheath, so the inner boundary of that bump corresponds to the magnetopause. In the plot of the x-component of

the velocity, the magnetopause is seen as the location where the value goes to 0, since the plasma from the solar wind is diverted around the magnetosphere at the magnetopause. Finally, in the plot of the z-component of the magnetic field, there is an almost imperceptible shift at  $11 R_E$ . So in this case, counterintuitively, it is easier to find the magnetopause in the plasma results for the simulation than in the magnetic field results.

### **C. Empirical Fit**

In this lab, students find the subsolar point of the magnetopause for a variety of plasma conditions and fit their data to Eq. 5, finding their own value to compare to the leading constant of 107.4. The students run the simulations for two types of conditions. In one set, the solar wind speed is held constant and the solar wind number density is varied, and in the other set the fixed and varying parameters are switched. Most groups get good agreement between their leading constants for these two sub-groups. Some groups have had constants that were a bit high. Finding high values for the constant is not surprising since the students were given so much freedom to define their own method of determining the magnetopause location. More prescriptive directions on how to find the magnetopause location might yield better constants, but we are wary of losing the experience that the students gain by defining their own standards.

## **IV. SPACECRAFT DATA**

In this section of the lab, students search for magnetopause crossings for three sets of data chosen from several events and several spacecraft (Geotail, Polar, the GEOS satellites, and the LANL geosynchronous satellites). The students first compare the actual position of the spacecraft to the location of the magnetopause predicted by Eq. 6. Next, they examine the particle and magnetic field data from that spacecraft for signs that the spacecraft made magnetopause crossings at the predicted time or at other times. Finally, students compare the signs of magnetopause crossings that they see in the magnetic field and particle and discuss their perceptions of the difficulty of interpreting those two types of data.

### A. Magnetopause Crossing in Data

Figure 4 shows an example of the search for spacecraft crossings of the magnetopause, in this case Geotail, that students do in this lab. The data shown is from 31 October 2003. On that day a large CME hit Earth, causing auroras that were visible throughout much of the United States.<sup>19</sup>

The top panel of Figure 4 predicts several magnetopause crossings, but the most notable crossings are at roughly 5:00, 10:00, and 11:00. From 1:30–5:00 and from roughly 10:00–11:00, Geotail is predicted to be inside the magnetosphere. In other words, at those times Figure 4 shows the magnetopause further from the Earth than the spacecraft is. For most of the rest of that day Geotail was inside the magnetosphere. The data in the middle and bottom panels of Figure 4 shows the crossing from inside to outside the magnetosphere at 11:00 and the data also shows other magnetopause crossings, though as described below the crossings seen in the data differ a bit from the predictions.

The middle panel of Figure 4, which shows the ion flow velocity measured by Geotail and the x-component of the solar wind speed measured by ACE, has three visible regimes. During this day the x-component of the solar wind velocity slowly changes from  $-1200$  km/s to  $-800$  km/s. From 0:00–5:00 most of the Geotail ion flow velocity data is missing. From 5:00–11:00 the three components of the ion flow velocity measured by Geotail oscillate near values of  $-700$  km/s,  $-400$  km/s, and  $200$  km/s respectively. While from 11:00–24:00 the y- and z-components oscillate near  $0$  km/s, and the x-component is based at roughly  $-1000$  km/s, with spikes up to almost  $0$  km/s. The behavior of the x-component during this last time period can be interpreted as being due to the spacecraft being just outside the magnetopause in the magnetosheath. When the x-component is near  $-1000$  km/s it matches the solar wind speed, suggesting that Geotail is outside the magnetopause at those times. The noisiness of these measurements of the ion speed in the magnetosheath is likely due to reflection of the solar wind ions off the magnetopause and the movement of the magnetopause as the solar wind conditions vary.

The velocity measurements act much differently from 5:00–11:00, suggesting that the spacecraft is inside the magnetosphere during those times. Notice that during this time there are several short time periods where all components of the data have spike which match their magnetosheath values. This suggests that during this time period the spacecraft is near the magnetopause boundary and that fluctuations in the solar wind cause the magnetopause to oscillate back and forth across Geotail's position.



The bottom panel, showing Geotail's magnetic field measurements, has similar regions of behavior. From 0:00–11:00 all three components have spiky measurements which trend downward. The downward trend is due to the decreasing magnitude of the Earth's dipole field as Geotail gets further from Earth, while the spikes are due to disturbances in the plasma in the magnetosphere during this magnetic storm. From 11:00–24:00, the three components are steadier and oscillate near 10 nT, 5 nT, and  $-10$  nT, respectively. During this time Geotail is in the magnetosheath where the solar wind magnetic field dominates. Note that during several of the spikes in the magnetic field which occur between 0:00 and 11:00, that the magnetic field matches the magnetosheath values. This supports the idea that the magnetopause oscillated back and forth past the spacecraft, as was mentioned with the ion velocity data.

In summary, the spacecraft data (bottom two panels of Figure 4) show that Geotail crossed the magnetopause. The data suggest that Geotail was inside the magnetopause from 0:00–11:00 (though there were some brief crossings during that time), and that it was outside the magnetopause from 11:00–24:00. This is a slightly different story than what the top panel of Figure 4 predicted. The prediction had a more complicated series of crossings up until a final crossing to the outside of the magnetopause at 11:00. Overall though, the predicted and actual crossings agree fairly well.

## **B. Results**

The students get reasonable results for this section of the lab. As seen in the example in Sec. IV A, finding the magnetopause crossings in the data can be a complicated process, so the students do typically need a bit of guidance as they proceed. One of the things that troubles some of the students is that some of the data sets they examine contain no magnetopause crossings. This disconcerts students since their expectation is that all data sets will have crossings. In research there are often data sets that do not contain the phenomenon being searched for, so it is good to have students do some cases of this sort.

In general, the students do a good job of finding the crossings in the magnetic field data, but they have more difficulty with the particle data. These problems are to be expected since in most of the cases the ion data is not as clear as in Figure 4. This problem could be alleviated somewhat by finding events where the signs of the magnetopause crossing are clearer in the ion data, as well as by giving the students more guidance in the interpretation of the ion data.

## V. CONCLUSION

We have presented a lab in which students examine the Earth's magnetopause using simulations and spacecraft data. In this lab students are challenged by exposure to an active area of research that they might not otherwise encounter as undergraduates. Furthermore, not only are they exposed to space physics, they work on a problem using real data and tools in a manner that is not far removed from what current researchers do. Experiences of this sort are key in retaining physics majors and in helping physics students determine what they want to do with their physics education.

The outlook for future space physics and astronomy labs involving nearly current research topics is bright. The move toward open access to spacecraft data, coupled with the increase in the number of operational spacecraft taking science data, continues to broaden the areas of space that anyone with an internet connection can have access to. On the simulation side, the development of efforts to give public access to supercomputers, along with the steady increase in computing power, continues to expand the number of problems that anyone can find the resources to simulate. The key difficulty to applying these new observational and computational powers to the teaching lab remains formulating appropriate problems for students to examine.

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## Acknowledgments

We would like to thank Kristi Keller from NASA Goddard Spaceflight Center. Conversations with Kristi led to the development of this lab. Simulation results have been provided by the Community Coordinated Modeling Center at Goddard Space Flight Center through their public Runs on Request system. The CCMC is a multi-agency partnership between NASA, AFMC, AFOSR, AFRL, AFWA, NOAA, NSF and ONR. The BAT-R-US Model was developed by Tamas Gombosi et al. at the Center for Space Environment Modeling at the University of Michigan. Spacecraft key parameter data provided by CDAWeb. Data shown here from Geotail MGF provided by S. Kokubun at STELAB, Nagoya University, and Geotail CPI provided by L. Frank at University of Iowa. Solar wind data shown here is from ACE SWEPAM provided by D. J. McCo-

mas from SWRI and ACE MFI provided by N. Ness from Bartol Research Institute. This research was supported by an award from Research Corporation.

## Figure Captions

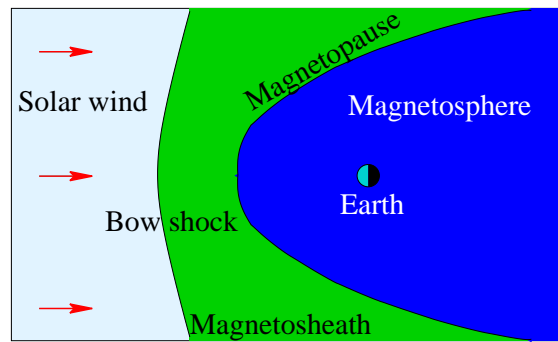


FIG. 1: The Earth's magnetosphere.

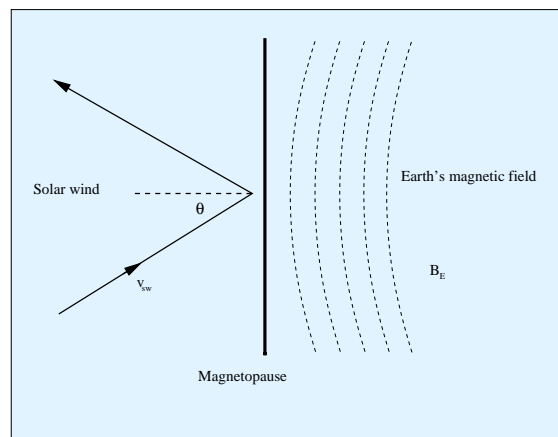


FIG. 2: The pressure balance at the magnetopause between the solar wind dynamic pressure and the Earth's magnetic pressure.

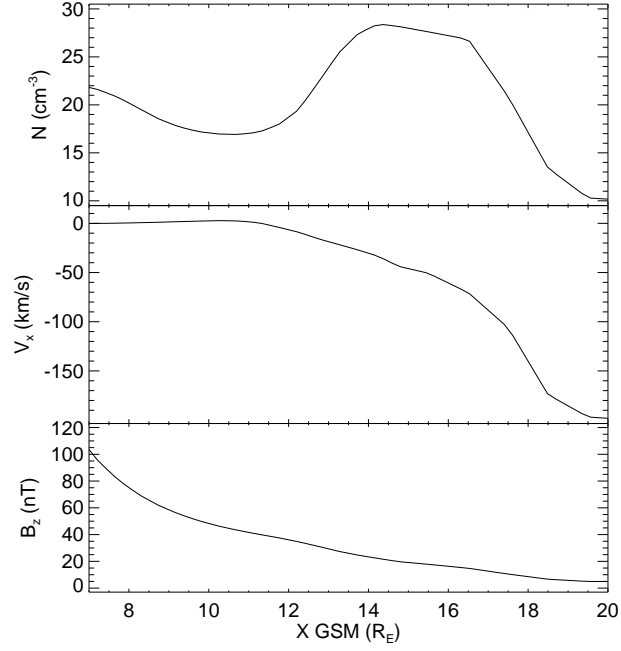


FIG. 3: Simulation results plot used to find subsolar point of the magnetopause. The data are from five minutes into a typical simulation run and they are plotted along the line from the Earth to the Sun. The top panel shows the number density, the middle panel shows the x-component of the plasma flow velocity, and the bottom panel shows z-component of the magnetic field. Geocentric solar magnetospheric (GSM) coordinates are used here. In this system the x-axis points from the Earth to the Sun, the z-axis points in the direction of Earth's north magnetic pole, and the y-axis completes the right-handed system.<sup>20</sup>

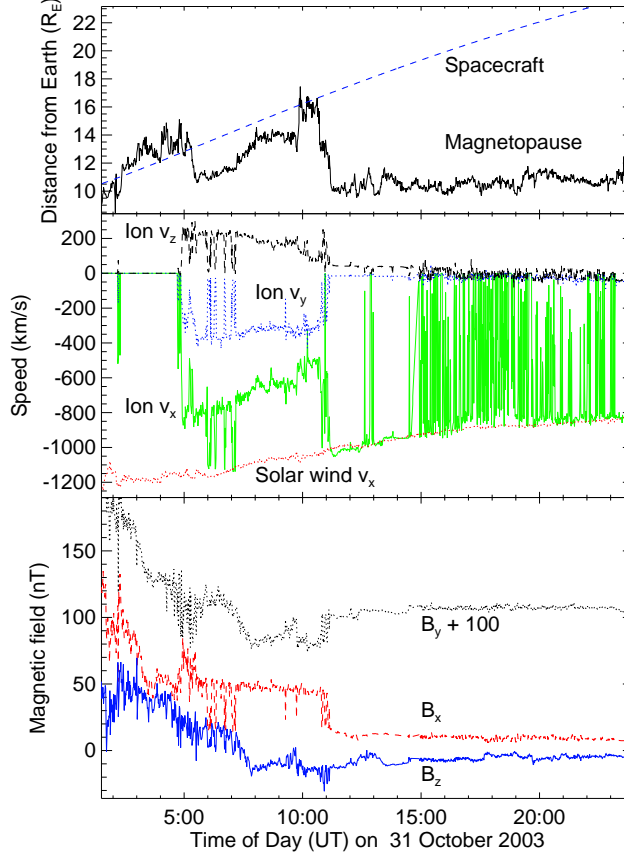


FIG. 4: Plots showing Geotail's magnetopause crossings on 31 October 2003 (color online). The top panel shows the Geotail spacecraft's distance from Earth and the predicted location of the magnetopause along the line from the Earth to Geotail based on the ACE spacecraft measurements of solar wind conditions. The middle panel shows Geotail's measurements of the ion flow velocity and the x-component of the solar wind speed measured by ACE, all in geocentric solar ecliptic (GSE) coordinates. In this system the x-axis points from the Earth to the Sun, the z-axis points perpendicular to the plane of earth's orbit, and the y-axis completes the right-handed system.<sup>20</sup> The bottom panel shows the three components of the magnetic field measured by Geotail in GSE coordinates. Note that 100 nT has been added to  $B_y$  in order to separate the lines on the plot.